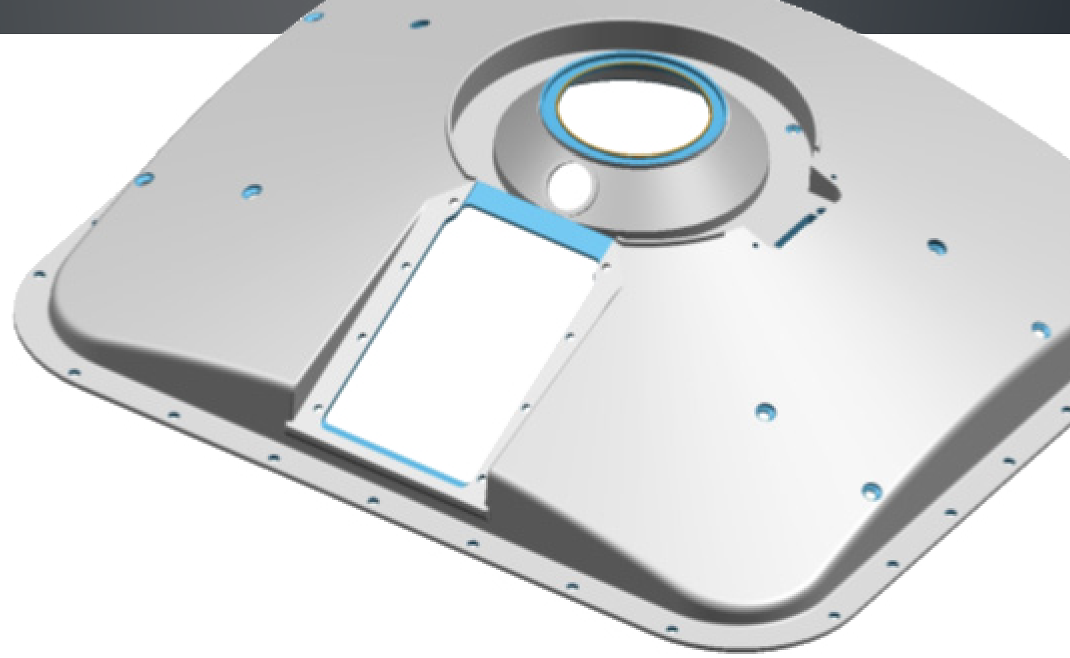
CARPENTER ADDITIVE®

AEROSPACE

CASE STUDY

PIXL MARS ROVER

Precision additive manufacturing for mission-critical performance



SUMMARY

Function-focused design leads to additive manufacturing possibilities

The Mars 2020 mission with its Perseverance rover is part of NASA's Mars Exploration Program, a long-term effort of robotic exploration of the Red Planet. The mission addresses high-priority science goals for Mars exploration, including key astrobiology questions about the potential for life on Mars.[1]

An important component of Perseverance, launched in July 2020, is the Planetary Instrument for X-ray Lithochemistry (PIXL). Mounted on a turret at the end of the robotic cantilever arm, the PIXL assembly was designed by engineers at the NASA Jet Propulsion Laboratory (JPL) to perform precision chemical analysis and experiments in a physically demanding and hostile environment. The instrument package designed by JPL focused 100% on the functionality of the components rather than taking traditional considerations toward manufacturability. Only after the team had the optimal design to carry out the required functions did they turn to the question of how to produce the components.

End-to-end additive manufacturing expertise iterates to success

The created design, with its focus on function and weight savings, included features that prevented traditional manufacturing methods from offering a clear path to production. The JPL team turned to Carpenter Additive hoping to take advantage of the design flexibility afforded by powder bed fusion 3D printing.

The Carpenter Additive team successfully developed the final assembly components within the defined parameters. Many iterations were required along the way, as even additive manufacturing faced challenges on the long path to manufacturability. Hopeful for a six-month project, the demanding journey was completed in 18 as the team iterated to fail fast, learn and establish new best practices from these successions, and implement improvements at every stage of production, from material selection and printing to inspection and machining.

[1] *https://www.jpl.nasa.gov/missions/mars-2020-perseverance-rover/*

BY THE NUMBERS

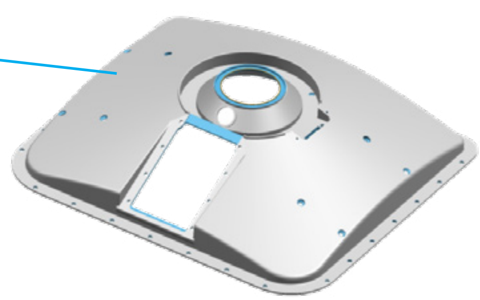
MAIN OBJECTIVE	Measure the chemical makeup of rocks at a very fine scale
LOCATION	Mounted on the turret at the end of the robotic arm
MASS	Arm-mounted sensor head: Nearly 10 lbs (4.3 kg) Body-mounted electronics: ~ 6 lbs (2.6 kg) Calibration target: ~ 0.033 lbs (0.015 kg)
POWER	~ 25 W
VOLUME	Arm-mounted sensor head: ~ 8.5 x 10.5 x 9 in (21.5 x 27 x 23 cm)
DATA RETURN	~ 16 Mb per experiment, or ~ 2 MB per day
TRAVEL SPEEDS	468 ft (152 m) per hour
ENVIRONMENTAL CONDITIONS	Surface temperatures ranging from -100°F (-73°C) to +70°F (21°C) Dust-carrying winds from 10-20 mph (16-32 km/h)
TYPICAL PART FLATNESS REQUIREMENTS	0.003 in (0.076 mm)
MATERIAL	Ti 6Al-4V, Grade 5+ tailored for EB-PBF applications

CARPENTER ADDITIVE CONSTRUCTED THIN-WALLED, TIGHT TOLERANCE COMPONENTS WITH PRECISION MACHINED FEATURES

Front Cover

Large, thin-walled panel

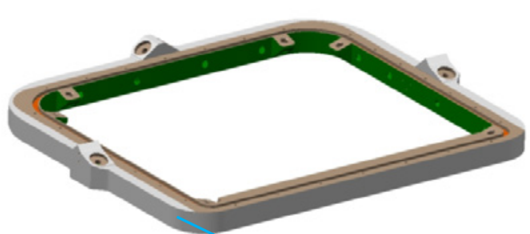
- 7.2 x 8.1 x 0.030-0.040 in. wall thickness
- 183 x 206 x 0.76-1 mm wall thickness

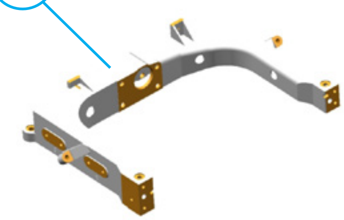


X-Ray Bench and X-Ray Bench Support

Hollow, thin-walled brackets for precision instrument mounting

- 3.7 x 5.8 x 0.9 x 0.030-0.045 in. wall thickness
- 94 x 147 x 23 x 0.76-1.1 mm wall thickness

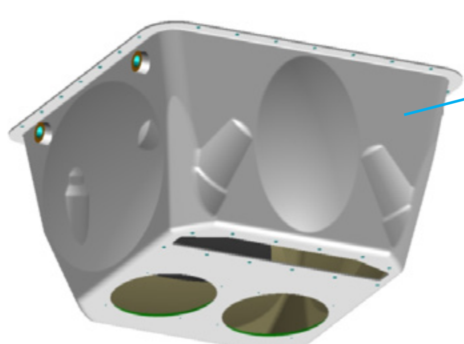




Mounting Frame

Hollow box beam structure

- 7.8 x 9.2 x 0.030-0.045 in. wall thickness
- 198 x 234 x 0.76-1.1 mm wall thickness



Back Cover

Deep, thin-walled box structure

- 7.2 x 8.1 x 4.3 x 0.015-0.045 in. wall thickness
- 183 x 206 x 109 x 0.38-1.1 mm wall thickness

Surviving space travel

The precision engineering used to design the PIXL created several challenges for its construction. The instrument package was designed to withstand lots of trauma. Launch stresses are demanding on a payload, so the design had to withstand extreme shock and vibrations before spending seven months travelling through frozen space. After landing on the planet's surface, the rover will spend two years roving very rocky terrain in extremes of both hot and cold with wind and sandstorms attempting to erode its surfaces.

Beyond the challenges posed by the Martian environment, the PIXL itself is located on the end of the cantilever arm on top of the hammer drill in one of the most extreme positions on the rover. To ensure components built by Carpenter Additive met the no-fail requirements, the team was required to deliver several of each part: a flight component, a test bench component, and one or more additional components for destructive testing analysis by NASA.

Staying on mass budget

Weight was a critical factor in the design of the entire Perseverance rover. All components were collectively required to stay below an absolute weight maximum, otherwise the rover wouldn't be able to launch. A key challenge was to stay within the assigned mass budget. Any exceeding weight on the critical instrument could cause other experiments to be dropped, so mass budget was repeatedly the top consideration when weighing possible design changes throughout the process.

> "Touching down on Mars can best be described as a highly engineered, controlled crash landing, and these parts have to withstand that force and then carry out precision experiments."
>
> —Ken Davis, Director of Additive Technology, Carpenter Additive

The right powder bed for the job

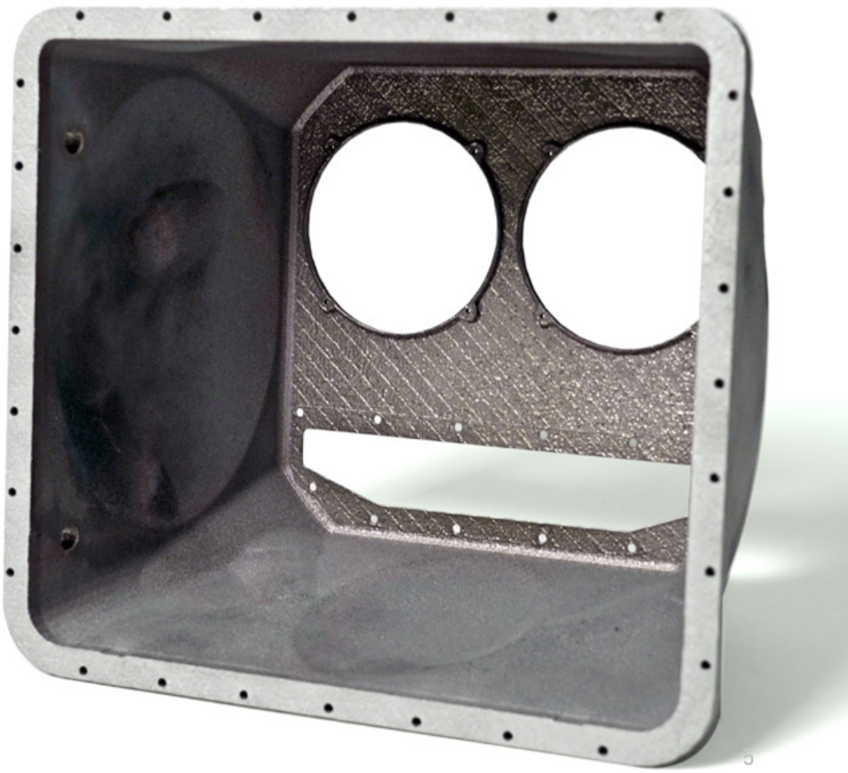
While the front and rear covers resemble sheet metal components that could be deep drawn, hydroformed, or superplastic formed, they include varying wall thicknesses that can only be achieved through additive manufacturing. The complex surfaces bulge outward in some areas and inward in others, allowing clearance for instruments both within and outside of the PIXL experiment package. The X-ray bench, bench support bracket, and frame were all hollow box beams. As hollow components, they added additional complexity because of their very thin wall thicknesses, down to about 0.045 in. (1.1 mm) at their thinnest points.

With two prevailing powder bed technologies to choose from, the experts at Carpenter Additive's production facilities chose to move forward with Electron Beam Powder Bed Fusion (EB-PBF) to manufacture the PIXL's components. While Laser Powder Bed Fusion (L-PBF) is typically considered better at thin walls, fine features, and smooth finishes and EB-PBF excels with larger, heavier, and thicker parts, other process advantages led the team to choose the latter.

Because it is a hot process, the electron beam chamber keeps the component packed in powder at a high temperature during the multi-day build and cooling slowly over 12 hours, helping to remove residual stresses that could distort fine features. Additionally, as the powder bed itself is semi-sintered through the processes, it acts as a support structure during the build. This eliminated the need to print supports attached to the surface of the components and risk not meeting the very tight tolerances required by the application specs.

"Often, when we evaluate the two technologies, there is a clear 'winner' for manufacturing, but this was a tight race throughout, with EB-PBF winning by probably an unofficial 52/48 margin."

—Ken Davis, Director of Additive Technology, Carpenter Additive



Material experts optimize for performance

Choosing the right material, or in some cases developing custom powders, is essential to the success of a build and the final performance of a component. With over a century of materials science expertise and a team of staff metallurgists, Carpenter Additive was uniquely positioned to maximize performance through targeted material selection.

The mixture of strength and light weight dictated the use of titanium, and Ti 6Al-4V Grade 5+ was chosen for its improved mechanical properties. The higher strength and very good ductility provided a minimum 135 ksi yield strength at minimum 15% elongation in the highly stressed, very thin parts.

Expertise during every step of the process

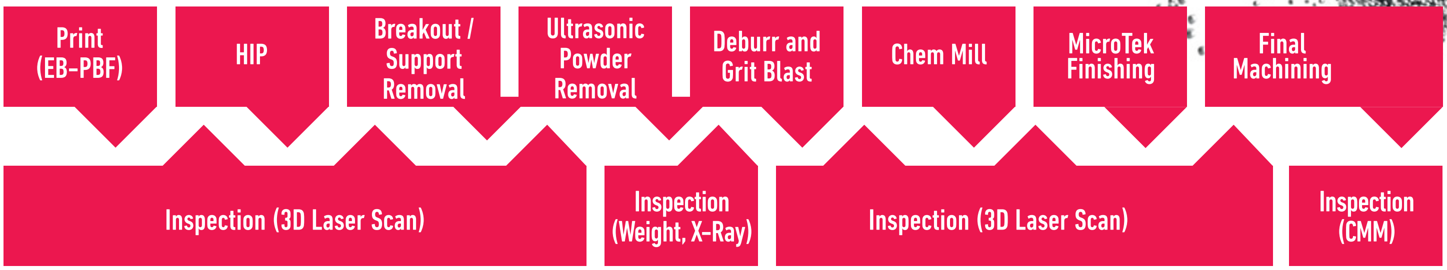
The Carpenter Additive team established a manufacturing plan for the critical PIXL components through a complex combination of additive and subtractive production techniques combined with innovative surface finishing. 3D scanning inspection played a critical role for the team to verify results after each process step.

“It was a long journey of mechanical processing followed by inspection, but because of all the fine features, we had to know if or how much we were deviating from the final part model to track our path forward,” Davis stated. “We used our HIP to homogenize the microstructure, but it’s a high temperature process that could distort the part, so we had to go back to the 3D scan. Deburring and grit blasting smooth the surface but can change dimensional features, so we go back in for inspection.”

The expert understanding of each process step, its potential to introduce deviations from spec, and how each affects the next was essential to the successful construction of the part family as the team overcame challenges along the way.

Proven manufacturing processes

AEROSPACE AM PARTS PRODUCTION IS A COMPLEX COMBINATION OF ADDITIVE AND SUBTRACTIVE MANUFACTURING PROCESSES, COMBINED WITH INNOVATIVE SURFACE FINISHING TECHNIQUES



Powder removal

Extraction of any residual powder is critical to avoid introducing a potential source of foreign object damage (FOD). The design of the hollow X-ray bench support provided only small holes as access to internal powder. No changes to the size or location of the holes was possible since their design was dictated by the load path, so an advanced powder extraction technique was required. Utilizing ultrasonic powder extraction, where a transducer on component finds the natural frequency of the internal powder cake to break it apart for removal, the team was able to extract an additional 156 grams of powder after already completing aggressive mechanical powder removal. The ultrasonic process, however, introduced its own challenges, as the natural frequency of the powder cake changes continually as it breaks apart, requiring re-tuning to chase the natural frequency until all powder is broken apart and removed.

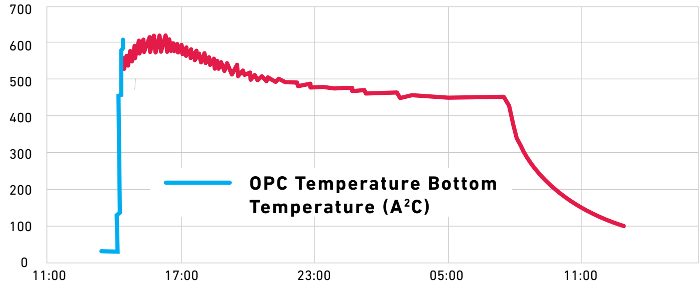
Chemical milling, used for several purposes including surface finish improvements and wall thinning, also flushed hollow components to ensure all residue powder was removed.

Scale factors

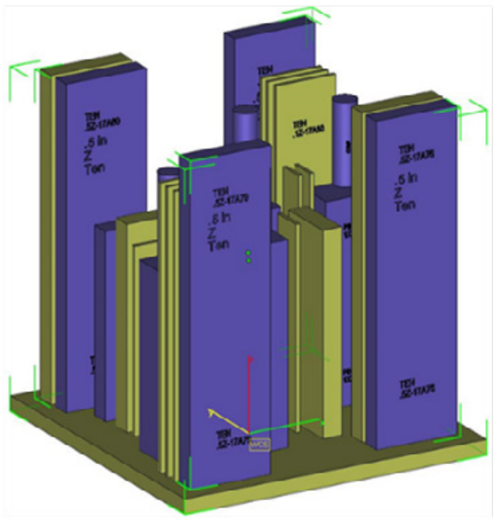
The EB-PBF process is a complex sequence of heating, expansion, melting, consolidation, solidification, and shrinkage. This is not, however, a linear process, and the team had to develop scale factors as the average values derived from comparing finished dimensions to model dimensions. Build temperature falls during the initial layers and recovers during the build, while top layer temperatures continue to increase in tall builds. This causes varying part temperatures throughout the build chamber. If these scale factors are not fully understood and the part is not designed with this in mind, features may start to grow away from the model and be stretched out of tolerance.

Because components are often rotated within the powder bed for optimal printing orientation, the parts were not uniformly "scaled" in each orthogonal axis. One axis dimension on the component is a compound of several axes in the printer, so several scale factors of x, y, and z contribute to dimensional accuracy. The thin walls of the PIXL parts created a very low thermal mass compared to typical EB-PBF components and proved to be a challenge in re-scaling, causing initial parts to be "over scaled" and printed too large. However, learning this lesson on the first part allowed the team to apply the knowledge to the other components, speeding up the iteration process moving forward.

TYPICAL TEMPERATURE PROFILE AT THE BOTTOM OF THE POWDER BED



DERIVING X, Y, AND Z SCALE FACTORS TO IMPROVE DIMENSIONAL ACCURACY

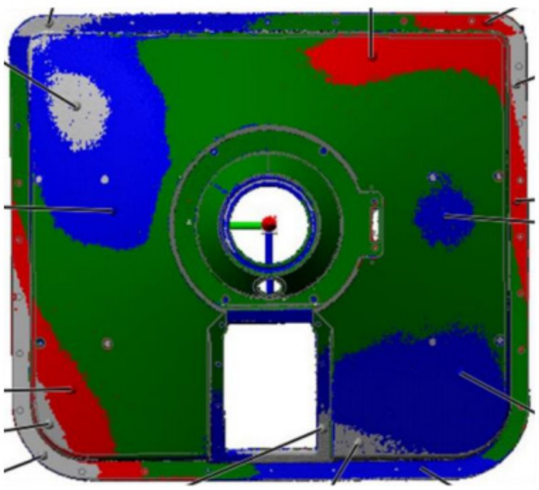


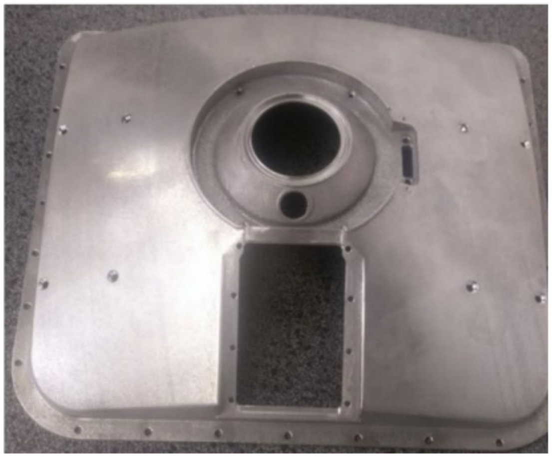
Robust supports to protect components

Supports play many roles in the printing and post-processing of additive parts, causing permanent and semi-permanent rigid supports to be the focus of much experimentation throughout development. During the printing operation, supports act as thermal shunts to dissipate heat and allow rapid solidification of the melt pool, they prevent part movement or distortion from thermal stresses, and they support overhanging features. Semi-permanent supports were employed to protect parts through several post-processing operations to prevent the distortion of thin-walled structures during HIP'ing, to allow for clamping during the machining of critical surfaces, and to hang parts in chemical milling.

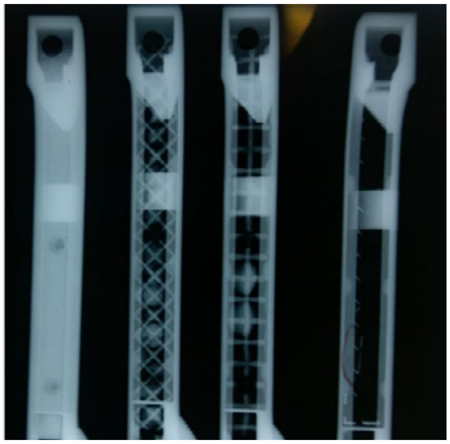
The box beams of the frame created a challenge because, regardless of orientation, one beam in the design would always be perfectly horizontal, requiring the top surface to be supported inside the hollow design. However, the design only allowed for 5 mm extraction holes for any internal material. After much experimentation with removable options, permanent supports were integrated into the design with the concession of a few grams to the mass budget. A lattice structure was printed on one leg of the frame after experimentation and optimization of the lattice to ensure it would survive printing, machining, and its mission on Mars. The results determined by experimentation on the box beams were important for the much larger frame component, again allowing the team to speed up their iterations through lessons learned.

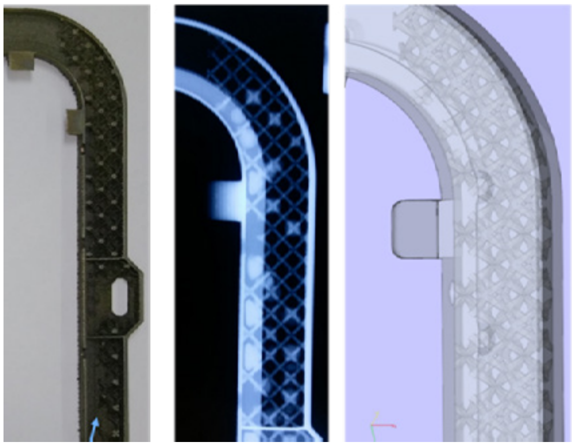
UNSUPPORTED PART SHOWING LARGE DISTORTION DURING HIP





X-RAY IMAGE OF SEVERAL VARIATIONS OF LATTICE SIZE AND WAFER SUPPORTS TO OVERCOME HIPPING DISTORTION

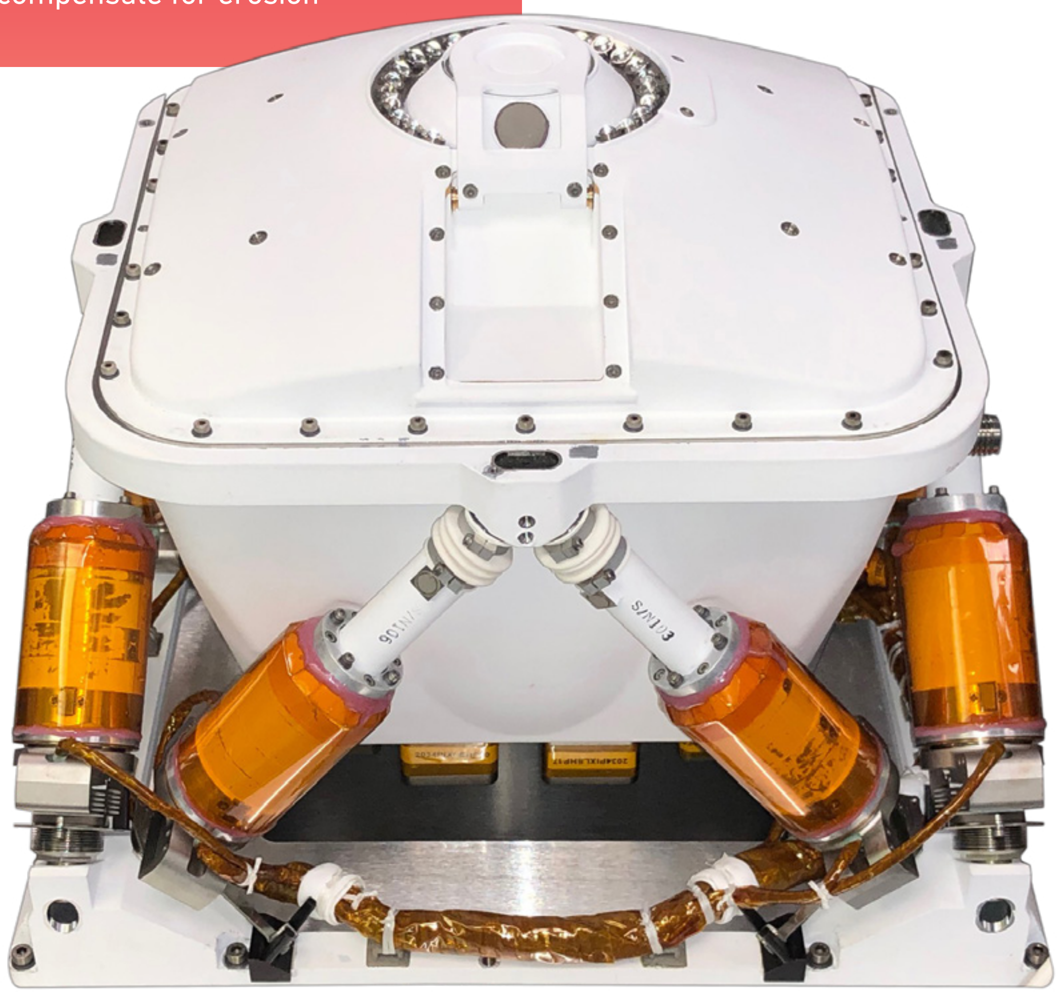




ADVANCING THE EVOLUTION OF ADDITIVE MANUFACTURING

The PIXL project challenged Carpenter Additive to problem-solve, iterate, and ultimately create novel additive manufacturing processes.

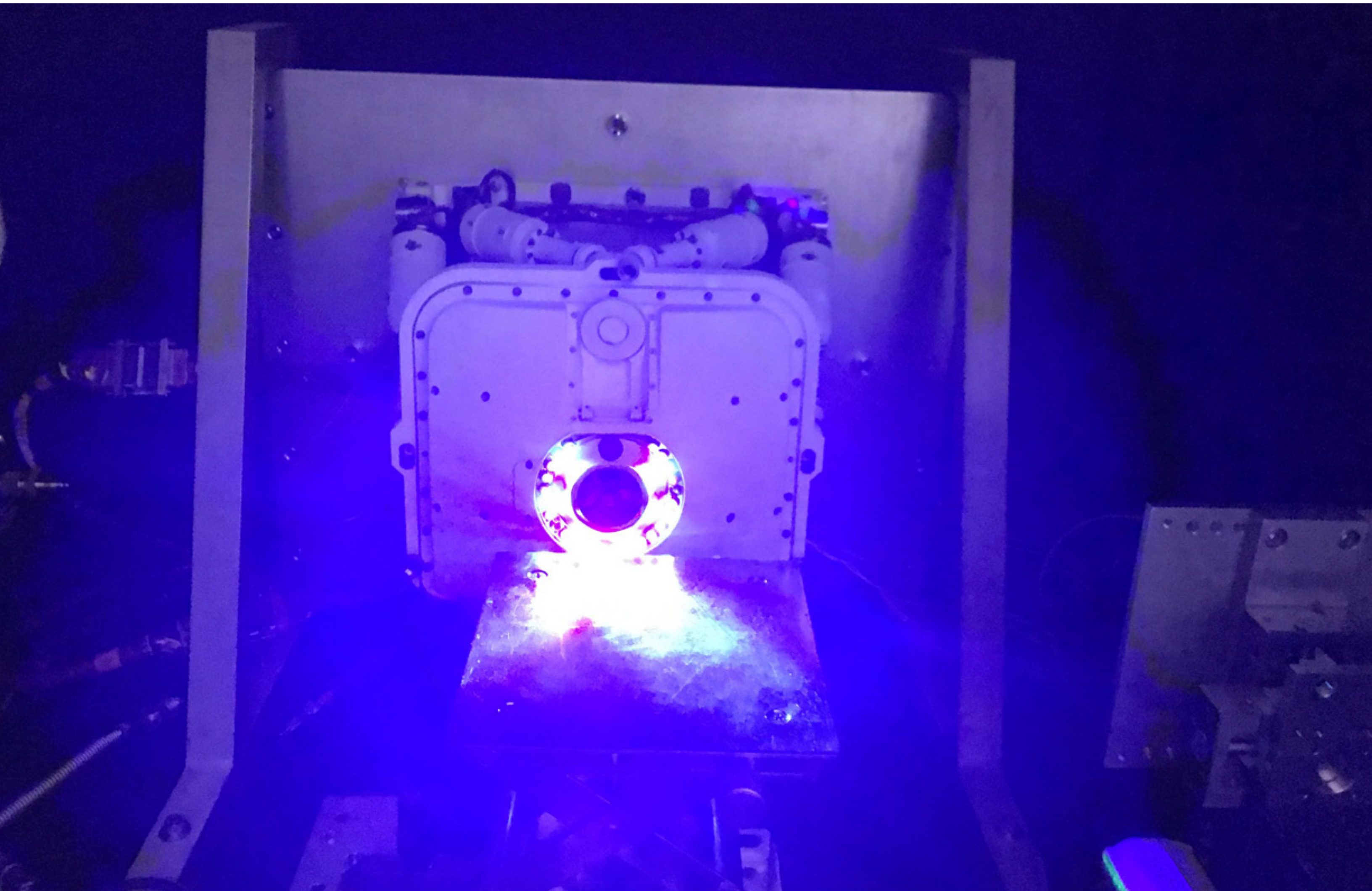
- Added stock on features and machined surfaces
- Optimized support structures
  - Refined supports to prevent distortion during HIP
  - Experimented with alternative internal supports to meet tight tolerances, including wafter fragmentation and permanent pin and lattice supports
- Pushed the limits of thin-wall strength
- Selectively thickened walls to compensate for erosion



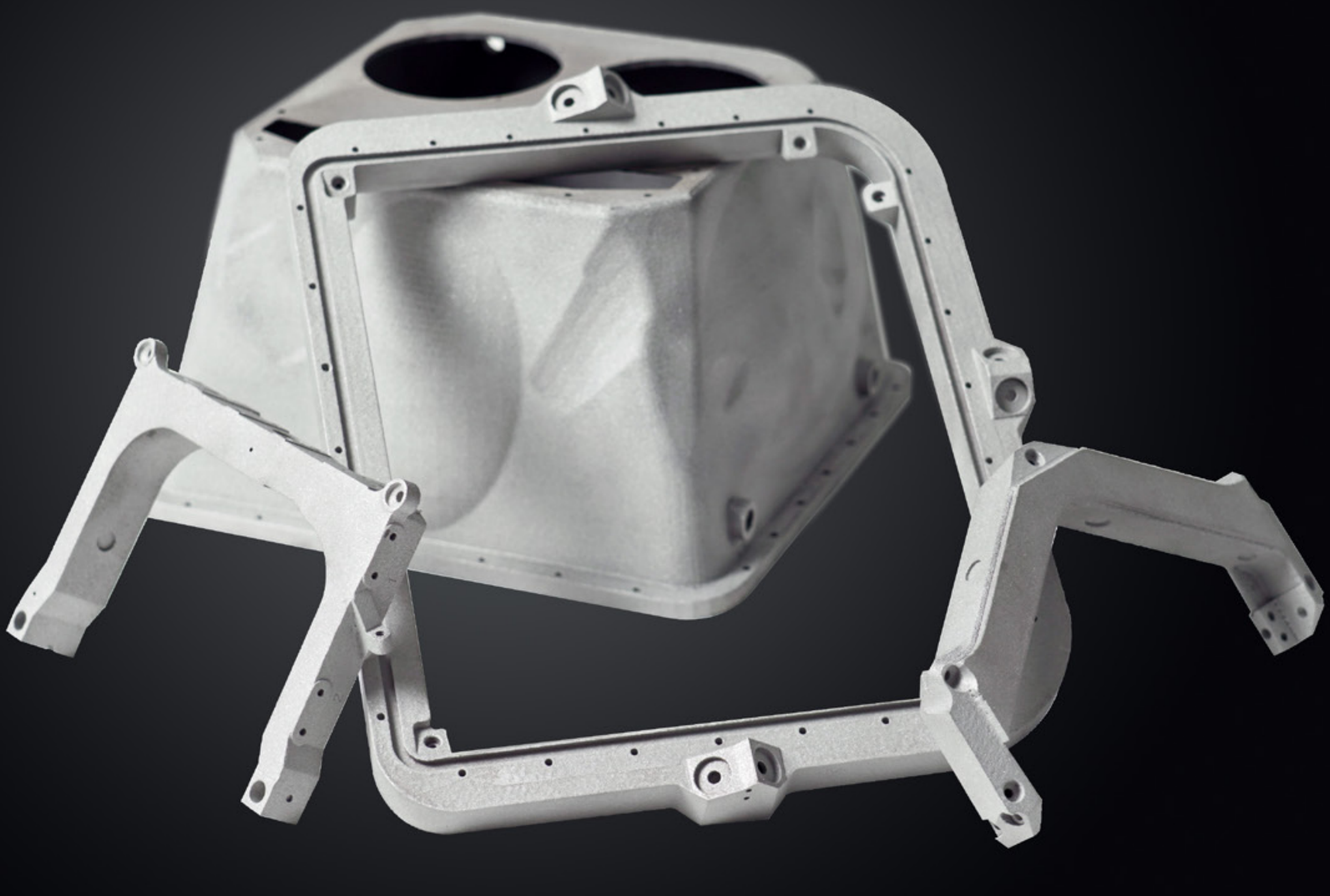
Precision manufacturing

Designed solely for function, the PIXL components were the most challenging Carpenter Additive had encountered. A part redesign was not possible, and tolerances could not be opened due to the critical mass budget. A total of .077 oz (22 g) was ultimately added to the 16 lb (7.26 kg) construction, within the margins to improve manufacturability. For instrumentation accuracy and hermeticity, high precision was required from the additive parts while very precise, fine machined details with 0.005 in. (0.127 mm) true position tolerances and a surface finish of 32µin Ra were achieved. The inspected mechanical properties provided greater than 130 ksi tensile strength at 15%+ elongation.

By February 2021, these components will arrive on Mars to support mission-critical, pioneering measurements of the chemical makeup of our neighboring red planet.



PIXL components are critical to the Perseverance rover's primary mission of finding signs of ancient life on Mars.



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Carpenter Additive is a fully integrated metal additive manufacturing partner for high-performance specialty materials and process solutions. From concept to creation, we collaborate with our customers to ensure success in critical aerospace, defense, transportation, energy, industrial, medical, and consumer applications.

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